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Action generation and action perception in imitation: an instance of the ideomotor principle

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We review a series of behavioural experiments on imitation in children and adults that test the predictions of a new theory of imitation. Most of the recent theories of imitation assume a direct visual-to-motor mapping between perceived and imitated movements. Based on our findings of systematic errors in imitation, the new theory of goal-directed imitation (GOADI) instead assumes that imitation is guided by cognitively specified goals. According to GOADI, the imitator does not imitate the observed movement as a whole, but rather decomposes it into its separate aspects. These aspects are hierarchically ordered, and the highest aspect becomes the imitator's main goal. Other aspects become sub-goals. In accordance with the ideomotor principle, the main goal activates the motor programme that is most strongly associated with the achievement of that goal. When executed, this motor programme sometimes matches, and sometimes does not, the model's movement. However, the main goal extracted from the model movement is almost always imitated correctly.

Keywords: imitation; ideomotor principle; action perception; action generation

1. INTRODUCTION

Imitation (when actors match their own movements to those of others) plays an important part in skill acquisition, and not merely because it avoids time-consuming trial-and-error learning. Observing and imitating is also a special case of the translation of sensory information into action. The actor must translate a complex dynamic visual input pattern into motor commands in such a way that the resulting movement visually matches the model movement, even when the motor output is only partly, or not at all, visible to the actor. For that reason, imitation is one of the most interesting instances of perceptual-motor coordination.

Although humans are very successful in imitating many complex skills, the mechanisms that underlie successful imitation are poorly understood. The translation problem is particularly interesting in children, because they must perform the translation despite the obviously great differences in orientation, body size, limb lengths and available motor skills. Additionally, these differences result in very different dynamic properties (e.g. Meltzoff 1993). Nevertheless, children spontaneously and continuously try to imitate the customs and skills manifested by the adults and peers in their environment.

The debate about whether the ability to imitate is learned (see Miller & Dollard 1941; Skinner 1953; Piaget 1962) or innate has a long history. Meltzoff & Moore (1977) concluded that the matching of others' visible movements with one's own movements is an inborn ability because it can be observed in neonates. Although some could replicate the finding of imitation in neonates (see Field *et al.* 1982; Vinter 1986; Reissland 1988; Heimann 1989; Meltzoff & Moore 1989), many others failed (Hayes & Watson 1981; McKenzie & Over 1983; Koepke *et al.* 1983; Neuberger *et al.* 1983; Lewis & Sullivan 1985) or showed that it is restricted to tongue protrusion (Kaitz *et al.* 1988; Heimann *et al.* 1989; Abravanel & DeYong 1991).[1]

Based on earlier findings, Meltzoff & Moore (1994) developed an influential theory—the theory of AIM—that assumes a supra-modal representational system, which merges the perceptual and the action systems. This supra-modal representational system is thought to match visual information with proprioceptive information. The AIM theory is in line with the recently common view that, in imitation, perception and action are coupled by a direct perceptual-motor mapping (see, for example, Butterworth 1990; Gray *et al.* 1991). In addition, AIM is the only theory, so far, that addresses the processes that allow the transfer of perceived actions into motor programmes.

A direct perceptual-motor mapping is also supported by neurophysiological findings. The so-called mirror neurons (di Pellegrino *et al.* 1992) in the monkey's pre-motor area F5 are potential candidates for a neural implementation of an observation–execution matching system, because they fire both during the observation and during the execution of particular actions. Support for a similar system in humans comes from the finding of a motor

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facilitation during action observation (Fadiga *et al.* 1995) and from increased brain activity in Broca's area during imitation (Iacoboni *et al.* 1999), an area that is thought to be the human homologue of monkey's pre-motor area F5.

Unfortunately, direct-mapping theories, including AIM, cannot account for certain findings in human imitation behaviour. For example, 18-month-old children not only re-enact an adult's action, but are also able to infer what the adult intended to do when the model fails to perform a target act (Meltzoff 1995). These findings suggest that young children comprehend the equivalence between acts seen and acts done not only on an inter-modal sensorial level, but also on a higher cognitive, intentional level. Although direct mapping can cope with *that* finding by making a few additional assumptions, *other* robust findings are harder to explain using direct-mapping approaches. Imitation, especially in children, sometimes consistently and systematically deviates from the model movements. First, it is well documented that although young children spontaneously imitate adults in a mirror-like fashion, older children tend to transpose left and right (Swanson & Benton 1955; Wapner & Cirillo 1968). Hence, if direct mapping is the basic process for imitation, it is either less 'direct' in younger children than in older ones (and that is not only counterintuitive but also contradicts the developmental function of direct mapping in theories such as AIM), or it should more appropriately be called 'direct mirroring' in younger children rather than 'direct mapping.' Second, a hand-to-ear test (originally developed for aphasics by Head (1920)) repeatedly showed that young children prefer to imitate both ipsi-lateral movements (e.g. left hand touching left ear) and contra-lateral (e.g. left hand to right ear) movements with an ipsi-lateral response (Schofield 1976). Clearly, it is not the movement (ipsi lateral versus contra lateral) that is mapped. But if body parts instead of movements were to be mapped onto each other, then in the case of contra-lateral movements imitated ipsi laterally (the so-called CI-error; see Bekkering *et al.* 2000) one of the two body parts involved would be mapped incorrectly—either hand or ear.

The reason for the avoidance of cross-lateral movements in children is not due to an immature bifurcation, as Kephart (1971) suggested. Recently, we showed that bimanual contra-lateral movements (i.e. left hand to right ear and, at the same time, right hand to left ear) are imitated contra laterally quite often and more frequently than unimanual contra-lateral movements are, even though the bimanual movements require a double crossing of the body midline and hence should be avoided even more, not less, often (experiment 1 in Bekkering *et al.* (2000)).

A replication of this standard experiment in which our imitation procedure was embedded in a song-and-dance game (see Appendix A for song text) allowed us to get more data per child, because we could repeat the original imitation procedure (consisting of the six hand movements three times each in random order) three times without losing the children's attention. As table 1 and figure 1 show, neither the relative amount of CI-errors, nor the relative lower amount of CI-errors with bimanual than with unimanual movements decreases with extensive practice ($T'_0 = 19$, $N_0 = 15$, $u = -2.86$, $p < 0.01$, Cureton test; see Lienert 1973).

Table 1. Average error rates for different error types and for each of three successive blocks. Friedman tests showed no difference in the error rates between blocks (overall: $\chi^2_r = 1.21$, d.f. = 2, $p = 0.294$, bimanual: $\chi^2_r = 0.32$, d.f. = 2, $p = 0.854$, and unimanual: $\chi^2_r = 0.03$, d.f. = 2, $p = 0.987$).

error type	block 1 (%)	block 2 (%)	block 3 (%)
overall rate	21.6	17.3	15.5
CI bimanual	14.5	14.0	12.3
CI unimanual	31.5	30.3	30.1

In a further experiment, we were able to show that unimanual contra-lateral movements are perfectly imitated contra laterally, if throughout the session only one ear is touched (experiment 2 in Bekkering *et al.* (2000)). Based on these findings, and supported by the observation that children almost always touched the correct ear (correct was defined in the mirror sense, because children spontaneously imitate ipsi-lateral movements in a mirror fashion), we speculated that children primarily imitate the goal of the model's action while paying less attention to, or not caring about, the course of the movement. However, if the goal is non-ambiguous (both ears are touched simultaneously) or if there is only one goal (only one ear is touched), then aspects of the movement come into play. In other words: in imitation it is primarily the goal of an act that is imitated; how that goal is achieved is only of secondary interest. Of course, perceiving the goal of an action would be a prerequisite for such a GOADI. Indeed, recent research showed that six-month-old infants already selectively encode the goal object of an observed reaching movement (Woodward 1998; Woodward & Sommerville 2000). Hence, these results demonstrate that in action observation children perceive the goals from a very early age.

We tested our proposal of GOADI by a variation of the hand-to-ear task that allowed the removal of the goal objects of the model's movement. Instead of touching the ears, the model now covered one of two adjacent dots stuck to the surface of a table with either the ipsi- or the contra-lateral hand (experiment 3 in Bekkering *et al.* (2000)). Results were similar to those of the hand-to-ear task. Children always covered the correct dot; but they quite often used the ipsi-lateral hand when the model covered the dot contra laterally. However, when the same hand movements were performed with the dots removed, children imitated almost perfectly ipsi-lateral with ipsi-lateral movements and contra-lateral with contra-lateral movements.

Thus, it seems that in imitation the presence or absence of goal objects for the model's movement has a decisive influence on imitation behaviour. Goal-oriented movements seem to be imitated correctly with respect to the goal; but the movement itself is frequently ignored. Movements without goal objects or with a single, non-ambiguous goal object are imitated more precisely. It seems that if the goal is clear (or absent), then the course of the movement plays a more central role in imitation. One might also say therefore, that the movement itself becomes the goal.

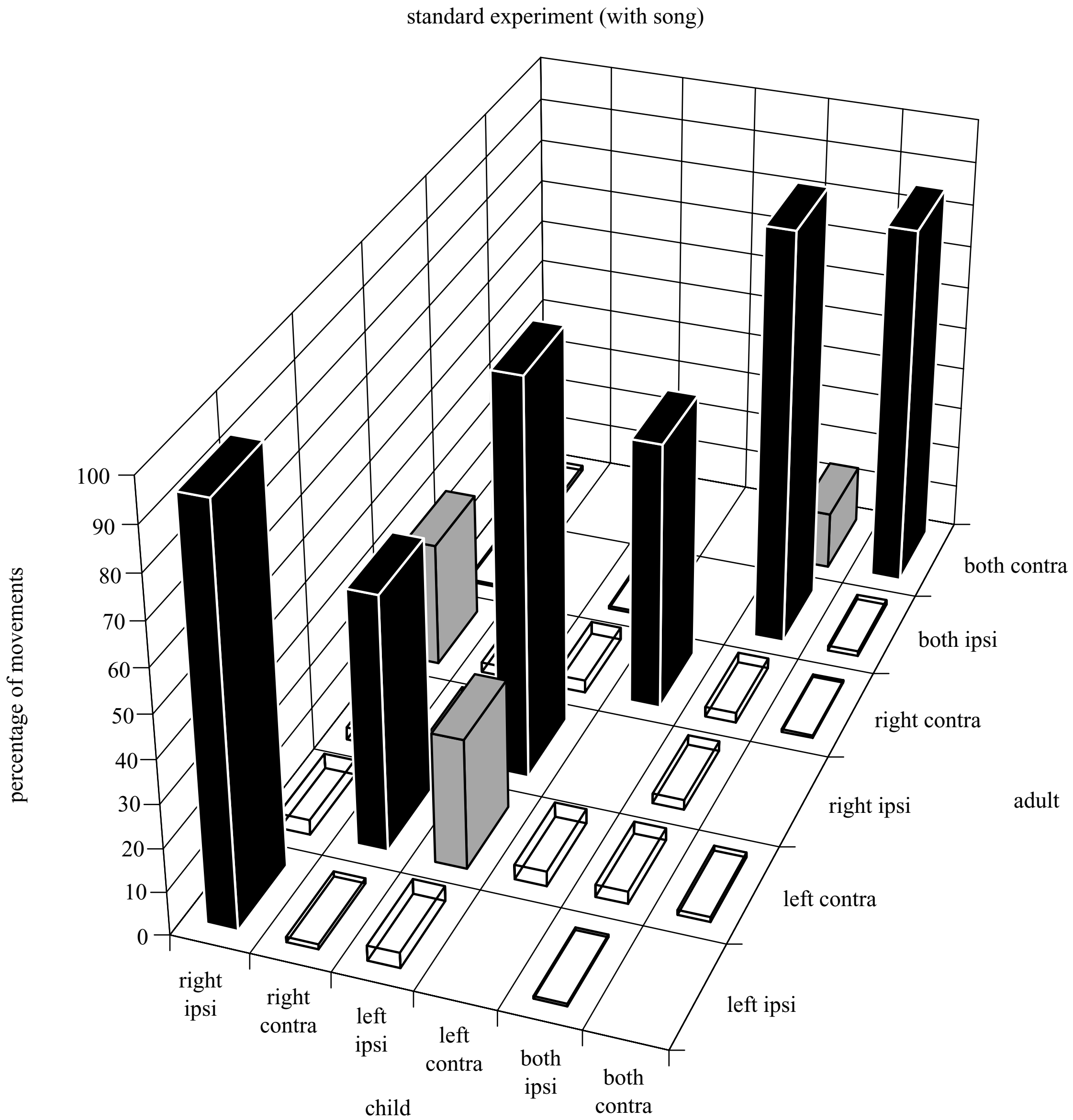


Figure 1. The movements made by an adult model on the right axis and the movements imitated by the child on the left axis. The black boxes on the diagonal represent the percentages of mirror-matching movements, the most frequent type of imitation for each model movement. The grey boxes represent the percentages of other types of imitation movement that deviated significantly from 0. Transparent boxes represent the percentages of types of imitation movement, which appear with statistically insignificant frequency (according to the Kolmogoroff test, setting $\alpha = 0.1$). Note that 'left' and 'right' are defined with respect to bodies. Thus, when a child 'correctly' mirrors a left-hand movement, he or she uses his or her right hand.

2. THE THEORY OF GOAL-DIRECTED IMITATION

Our theory of GOADI does not make a principled differentiation between object-oriented movements and movements lacking a goal object. It rather suggests:

(i) *Decomposition*. The perceived act is cognitively decomposed into separate aspects.
(ii) *Selection of goal aspects*. Owing to capacity limitations, only a few goal aspects are selected.
(iii) *Hierarchical organization*. The selected goal aspects are hierarchically ordered. The hierarchy of goals follows the functionality of actions. Ends, if present (e.g. objects and treatments of the latter) are more important than means (e.g. effectors and movement paths).
(iv) *Ideomotor principle*. The selected goals elicit the motor programme with which they are most strongly associated. These motor programmes do not necessarily lead to matching movements, although they might do so in many everyday cases.
(v) *General validity*. There is no essential difference in imitation behaviour between children, adults and animals. Differences in accuracy are due to differences in working memory capacity.

GOADI not only explains the imitation data, but also gives imitation a more functional nature. Direct mapping, however, has a rather automatic taste. GOADI allows imitators to learn from models even if the differences in motor skills or in body proportions are so great that the imitator is physically unable to make the same movement as the model. Whatever movement the imitator uses, the purpose of learning by imitation can be regarded as being fulfilled as soon as he reaches the same goal as the model.

GOADI is, however, primarily based upon very recent findings; and most of its assumptions still need to be tested. It is the aim of this paper to review the evidence for the theory in general and to provide further evidence by proving some of its specific assumptions.

3. GOAL SELECTION OR PERCEPTUAL DEFICIT?

In particular, we first have to examine whether the observed deviations in imitation behaviour might not be specific to imitation, but instead simply due to a perceptual discrimination deficit.

According to GOADI, in imitation the model's action is cognitively decomposed into sub-goals and goals, in the sense that the imitator can infer the intentions of the model (Meltzoff 1995; Woodward 1998).[2] Because the children we investigated almost always reached the correct ear or dot, one can be sure that they have perceived and represented the ultimate goal of the movement. However, one-third of the children showed no contra-lateral movements while imitating. Therefore, it remained unclear whether they had perceived and represented the course of the movement and simply did not consider imitating it because of its sub-goal status or, alternatively, whether they had not built up any representation of the movement's course.

If the error pattern we observed in imitation is due to a perceptual deficit, then children should experience difficulties in matching photographs depicting the end state of the movement. In particular, children should make more errors with photographs showing unimanual contra-lateral movements than with photographs depicting ipsi-lateral ones. Therefore, we showed photographs of an adult woman and a 3-year-old boy depicting the end states of the six movements used in the standard experiment. The experimenter randomly chose one photograph of the woman and asked the child to point to the photograph in which the boy showed the same movement by saying 'Wo macht der Bub das gleiche wie die Frau?' ('In which one is the boy doing the same thing as the woman?').

Figure 2 shows the frequency at which each of the six photographs of the boy was chosen for each photograph of the adult. We found that children produced an average error rate of 34.5%. When presented with unimanual photographs, children chose the matching photograph 51.7% of the time, which is well above chance level (25%, because there are four unimanual photographs and children virtually never matched bimanual photographs with unimanual ones) and more frequent than choosing non-matching ones (Friedman test, $\chi^2_r = 37.84$, d.f. = 15, $p < 0.001$). More important, the several types of error did not differ in their frequency of appearance, neither in general nor in particular for any of the four unimanual photographs of the adult (general: $\chi^2_r = 16.48$, d.f. = 11, $p < 0.124$, right ipsi and right contra: $\chi^2_r = 0.55$, $p < 0.761$, left ipsi: $\chi^2_r = 2.36$, $p < 0.307$, left contra: $\chi^2_r = 0.59$, $p < 0.744$, d.f. = 2 for all of the latter tests). Because the CI-errors (32.9%) were as frequent as IC-errors (34.5%), we conclude that there is no specific perceptual deficit for unimanual contra-lateral movements and that the particularly high error-rate for CI-errors (none the less leading to matching ears) specifically occurs under imitation and not in a more perceptually oriented task.

This interpretation must, however, be qualified. In the imitation task, the children saw the whole movement and not just the end state as in the photograph-matching task. It is probable that the error pattern in imitation also changes when children have to imitate static instead of dynamic models. Perhaps the dynamic part of the gesture is distracting; in this case, the children could even improve when imitating static models. Although Head (1920) has already demonstrated, at least for aphasics, that there is no fundamental difference between the imitation of real models and the imitation of their photographs, he did not analyse imitation behaviour using our methods. In addition, one cannot use photographs when investigating the role of the dynamic part of the model's act. Instead, one should use static real models, because otherwise the size and dimensionality (two-dimensional versus three-dimensional) would be confounded with the factor of interest: static versus dynamic model gesture. Thus, we decided to use an adult model instead of photographs to test the relevance of dynamic information in imitation tasks.

We used two variations of the standard experiment. In the first variant—the static or closed-eyes condition—children had to close their eyes during the movement phase of the model's gesture until the adult had reached the end position of the movement. When the model had reached the end position, she asked the child to open his or her eyes, and the child imitated the movement. If this condition—when compared with the data of the standard experiment—did not yield any difference in the error pattern, then the question would be if the dynamic phase of the model's gesture plays any role. Therefore, we introduced a second condition—the cueing condition. This was the opposite of the closed-eyes condition; more attention was drawn to the movement phase by first stretching the hand(s) used out towards the child, rather than moving it (them) directly to the ear(s): the model first stretched out the appropriate hand(s) straight (i.e. ipsi laterally) towards the child and waited until the child imitated that movement. Next, the experimenter moved the stretched-out hand(s) to the ear(s); and the child continued the imitation.

Thus, together with the standard experiment, we have three different levels of information about the movement phase: (i) no information in the closed-eyes condition; (ii) medium or normal information in the standard experiment; and (iii) salient information in the cueing condition. In addition, the cueing condition tests assumption (i) of GOADI, according to which the model movement is decomposed into several goal aspects. A fragmentation of the model movement should assist the decomposition of the model's act and, thus, reduce potential neglect of the movement aspect.

Figure 3 shows the frequency of each of the six imitated movements for each model movement in both conditions. In the closed-eyes condition, children generated 100.0%, 61.5%, 89.3%, 53.6%, 100.0% and 100.0% mirror-matching movements when presented with the left-ipsi,

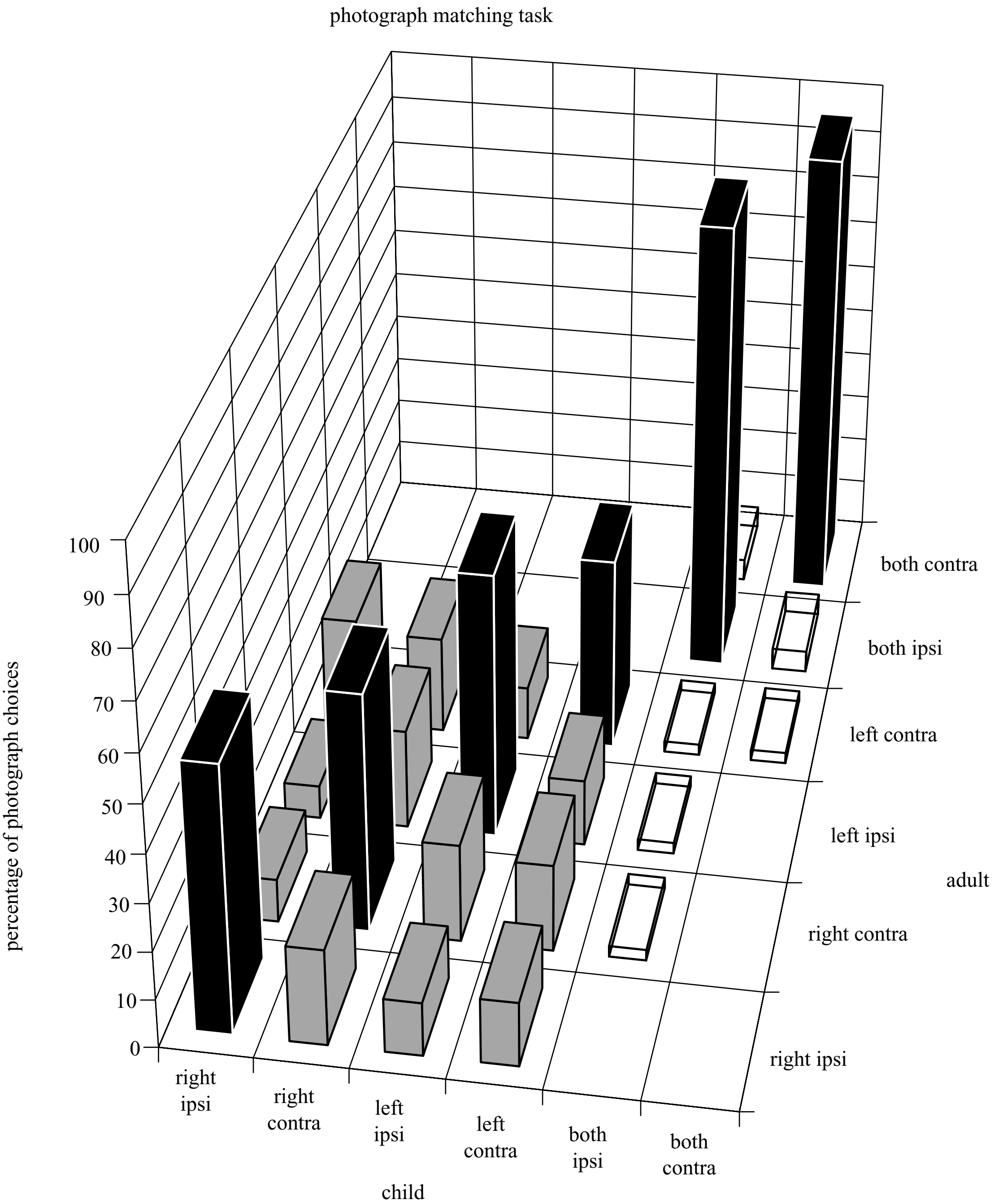


Figure 2. Results of a photograph-matching task. The adult's photograph presented by the experimenter is shown on the right axis and the boy's photographs chosen by the child on the left axis. The black boxes on the diagonal represent the percentages of matching choices, the most frequent choice for each of the adult's photographs. The grey boxes represent the percentages of other choices that deviated significantly from 0. Transparent boxes represent percentages of choices made with statistically insignificant frequency. Note that 'left' and 'right' are defined with respect to bodies. Thus, when the adult photograph depicts a right-handed movement, a correct choice would be the boy's photograph depicting the corresponding right-handed movement.

left-contra, right-ipsi, right-contra, both-ipsi and both-contra model movements, respectively. Again, we considered mirror-matching movements to be correct imitations. The children thus produced an average error rate of 16.0%. Only two types of error, both CI-errors, occurred with significant frequency: the left-handed ipsilateral imitation of the left-handed contra-lateral movement (38.5%) and the right-handed ipsi-lateral imitation of the right-handed contra-lateral movement (39.3%). Note that with these errors the ears touched by the child are still mirror matching the ears touched by the adult model. Unimanual CI-errors (average 38.9%) were as frequent for left-handed as for right-handed model movements ($T'_0 = 8$, $N_0 = 3$, $p = 0.375$, Pratt's exact test).

In the cueing condition, children always imitated the stretching of the hand(s) correctly. For the left-ipsi, left-contra, right-ipsi, right-contra, both-ipsi and both-contra model movements, they showed 96.3%, 92.6%, 82.1%, 74.1%, 92.3 and 92.6% mirror-matching movements. As in the previous experiments, we considered mirror-match-

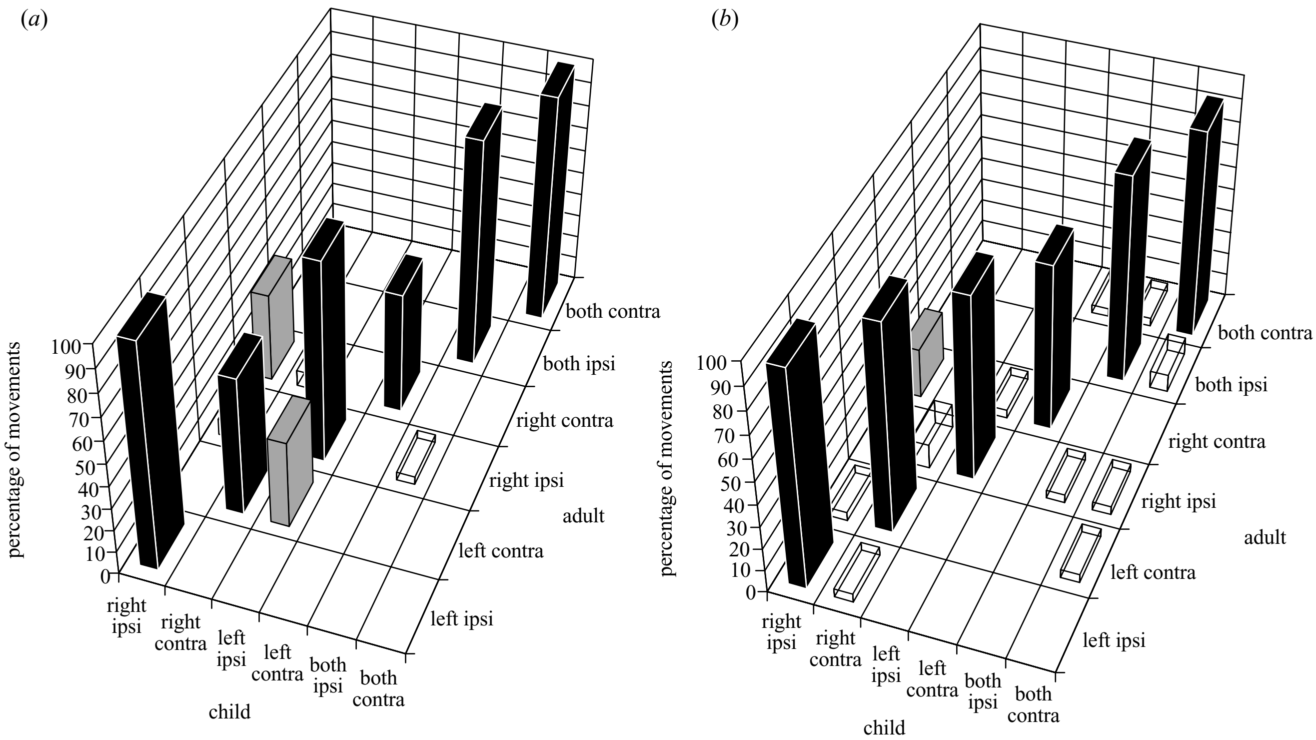


Figure 3. The movements made by the adult model on the right axes and the movements made by the child on the left axes. (*a*) The results of the closed-eyes condition, in which the children had to keep their eyes closed until the adult had reached the end positions. (*b*) The results of the cueing condition, in which the adult stretched out her hand(s) towards the child before moving it (them) to the ear(s). In this condition, the children also had to imitate the stretching of the hand. The black boxes on the diagonal represent the percentages of mirror-matching movements, the most frequent type of imitation for each model movement in both conditions. The grey boxes represent the percentages of other types of imitation movement whose frequency of appearance deviated significantly from 0. Transparent boxes represent percentages of types of imitation movement appearing with statistically insignificant frequency. It is important to note that 'left' and 'right' are defined with respect to bodies. Thus, when a child correctly mirrors a left hand movement, he or she uses his or her right hand.

ing movements to be correct imitations. Children thus produced an average error rate of 11.7%. However, here only one type of error, again a CI-error occurred with significant frequency: the right-handed ipsi-lateral imitation of the right-handed contra-lateral movement (22.2%). It is important to note that in this error the ear touched by the child is still the 'mirror match' of the ear touched by the adult model.

When compared with the cueing condition, the overall error rate of the closed-eyes condition was slightly, but not significantly higher ($T'_0 = 16.5$, $N_0 = 6$, $p = 0.375$, Pratt's exact test). However, an individual comparison of the two types of CI-error between conditions shows that the error rates were clearly higher in the closed-eyes condition (left CI-error: $T'_0 = 0$, $N_0 = 6$, $p = 0.001$, right CI-error: $T'_0 = 4$, $N_0 = 6$, $p = 0.05$). This can be seen in the complete absence of left-ipsi-lateral imitations of left-contra-lateral movements in the cueing condition.

The closed-eyes condition replicated the error pattern of the standard experiment: the main and only error types that occurred with significant frequency were CI-errors leading to mirror-matching ear contact. Thus, the movement phase of the gestures is neither necessary to cause the standard error pattern, nor distracting, because children did not improve in the closed-eyes condition.

In the cueing condition, the children imitated the stretching of the hand perfectly. This is what we expected, because hands were always stretched ipsi laterally. Moreover, cueing led to a reduction of the CI-errors. In fact, only one type of CI-error was left: the right-handed ipsi-lateral imitation of the right-handed contra-lateral movement. When this type of error occurred, children held the left hand stretched out in front of them (the mirror-matching imitation of the stretched right model hand) while touching the right ear with the right hand.

This (unexpected) type of error lends very strong support to GOADI. With this error type, children simultaneously imitated the sub-goal with the left hand and the main goal with the right hand. This not only shows that they decomposed the movement into goal and sub-goal, it also shows that both the goal and the sub-goal elicit their own, separate motor programme. The reason for the asymmetry of that error (it only occurred for right-handed contra-lateral model movements) is, however, unclear. It may have something to do with the fact that in that case the ear is touched with the dominant hand, a point we will return to later.

The above experiment shows that the imitator decomposes the model movement into several goal aspects. However, because sub-goal and goal were sequenced in time (a point we already commented on in Gattis *et al.* (1998)), it is unclear whether goals become goals because of their recency or because of their saliency. If goals were goals only because of their recency, then GOADI's assumption (iii) of a hierarchy of goals could simply be replaced by a recency effect.

To test assumption (iii) of GOADI, we used a new type of gesture (Gattis *et al.* 2002). Instead of touching her ears, the model now moved one hand either ipsi laterally or contra laterally to the left or to the right side of her head, just next to her ears (Gleissner (1998) and Gleissner *et al.* (2000) showed that, although the overall error rate decreases, the error pattern stays unchanged when moving the hands next to the ears instead of touching them). Just as her hand reached this position, she either clenched her hand into a fist or extended her fingers to open her palm. Thus, we introduced a new goal—open versus closed hand—that was reached at the same time as (not sequential to!) another goal, the position of the hand relative to the head. Because it is more salient, we expected the opening of the hand to become the main goal and the position of the hand relative to the head to become the sub-goal. If this were the case, then the children should make no (or hardly any) errors in the opening of the hand. By contrast, they should more or less ignore the position of the hand relative to the head, because the position of the hand relative to the head now should be a sub-goal.

Apart from testing whether in imitation children really extract the goals of the model's movement or whether they just imitate the most recent aspect of the movement, this experiment also tests whether the selection of a goal at the expense of a sub-goal only occurs for goals in space (left versus right). At present, the goals that the children pursued are always defined by a position in space, such as in the hand-to-ear task or in the experiment with the dots on the table (see Bekkering *et al.* 2000). If we are to develop a more general theory of imitation, it is necessary to show that its validity goes beyond spatially defined goals.

Figure 4 shows the frequency of each of the eight imitated movements for each model movement. We arranged the diagram in such a way that the mirror-matching movements are on the diagonal, because for each model movement the mirror-matching movements were the most frequently imitated movements (100.0%, 72.7%, 84.4% and 63.3% versus 93.9%, 78.8%, 84.8% and 72.7% for the left-ipsi, left-contra, right-ipsi and right-contra model movement with open versus closed hand, respectively). Based on our assumption that the mirror-matching movements are the correct imitations, we calculated that the children thus produced an average rate of error of 18.6%. For our further analyses of each model movement, we only considered erroneous movements of the child appearing with a frequency that significantly deviated from zero. No errors remained for the opening/closing of the hand. The overall error level was identical for both the open-handed and the closed-handed model movements (15.2%). Within each group of movements (open-handed versus closed-handed), the same five error types were left. These were the left-ipsi and left-contra imitations of left-contra movements, the right-ipsi imitations of right-ipsi movements, and the right-ipsi and right-contra imitations of right-contra movements (note that a 'correct' imitation would have required mirroring). None of these five types of error differed significantly between open-handed and closed-handed model movement conditions ($T'_0 = 0$, $N_0 = 1$, $p = 0.5$, $T'_0 = 10$, $N_0 = 2$, $p = 0.25$, $T'_0 = 10$, $N_0 = 2$, $p = 0.25$, $T'_0 = 11$, $N_0 = 4$, $p = 0.188$, $T'_0 = 0$, $N_0 = 4$, $p = 0.063$, for the respective types of error). Thus, we collapsed errors across open-handed and closed-handed movements for further analyses. Statistically, the five types of error occurred with equal frequency (10.6%, 9.1%, 10.6%, 18.2% and 12.1%, $\chi^2_r = 0.42$, d.f. = 4, $p = 0.981$). We further collapsed errors according to the categories: 'movement errors' (preserving the position of the hand relative to the head) and 'position errors' (preserving the type of movement, i.e. ipsi lateral versus contra lateral).[3] These two categories also did not differ in frequency (movement errors: 14.4%, position errors: 10.6%, $T'_0 = 29$, $N_0 = 9$, $p = 0.436$).

This experiment showed that the primary imitation of goals at the expense of sub-goals is not restricted to left–right tasks. When introducing a new, salient feature (an open hand with extended fingers versus a hand closed into a fist) in our standard paradigm, it is this feature that is now imitated without error. More importantly, the main goal of our earlier experiments, the position of the hand relative to the head, has now obviously become a sub-goal because it was erroneously imitated just as often as the former sub-goal 'type of movement'. In addition, we demonstrated that it is not the recency of a movement that makes it the main goal in imitation. The final spatial position of the hand was reached at the same time as the final configuration (open versus closed hand).

4. THE IDEOMOTOR PRINCIPLE IN IMITATION

Whereas the above experiments were primarily concerned with the perceptual component of imitation, the following experiment tries to investigate the motor component of imitation. According to GOADI, the model movement is decomposed into its different aspects. If this has taken place and if the imitator has (subjectively) decided on the main goal, our question here is how this goal is translated into the motor programme that (more or less erroneously) mimics the model's movement. In assumption (iv), GOADI states that the goal directly elicits the motor programme with which it is most strongly associated. This idea goes back to William James's analysis of voluntary actions (see Prinz 1990). If we want to elicit a voluntary action, we only need to think of the action's effects (e.g. pushing a button, grasping a cup, etc.), and the rest is accomplished by the motor system. The motor system, in turn, then uses the motor programme that has the strongest relation to the intended effect (this is the ideomotor principle). The strength of the association with the intended effect can be either innate or acquired through learning, in the sense that the particular motor programme is most frequently used to elicit the intended outcome.

Assumption (iv) of GOADI, however, still needed to be tested. We therefore varied the dot experiment (experiment 3 in Bekkering *et al.* (2000)) by replacing the dots with movable objects (see Wohlschläger & Bekkering 2002*b*). In the dot experiment, children had to imitate ipsi- and contra-lateral movements towards two adjacent dots stuck to the surface of a table. In addition to having replaced the dots with movable objects, we varied the character of the movement the model made towards these objects. In the experimental condition, the model grasped and lifted the objects. In the control condition, which was similar to the dot experiment (see experiment 3 in Bekkering *et al.* (2000)), the model almost touched the objects by

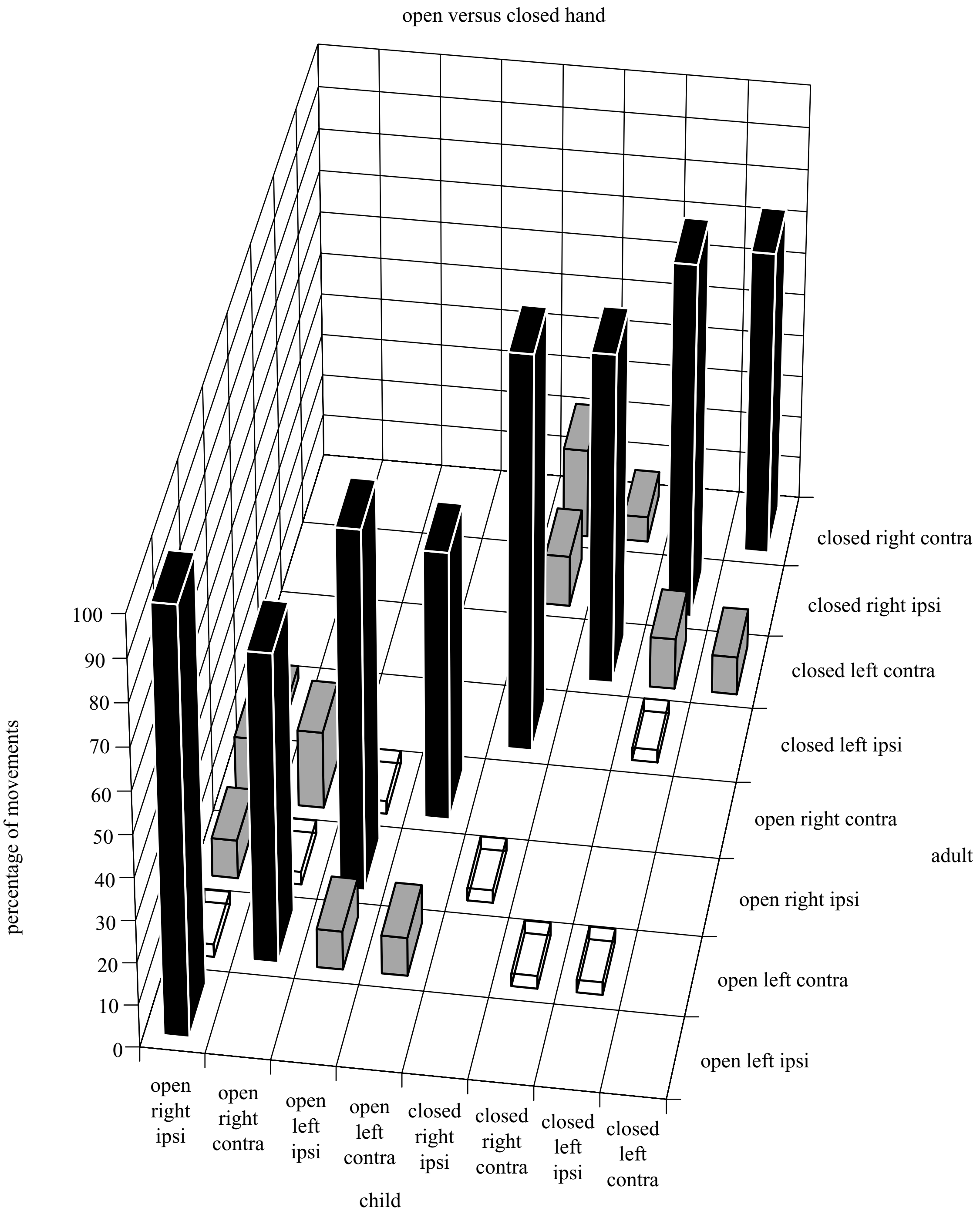
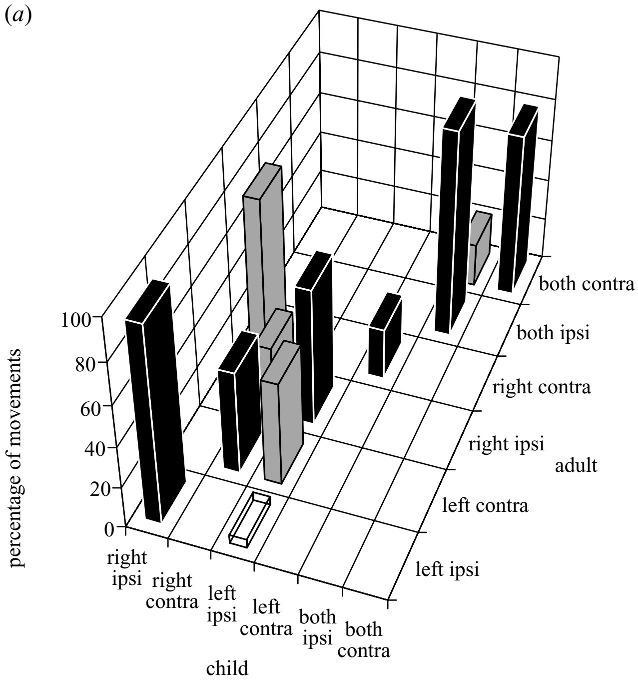


Figure 4. The movements made by the adult model on the right axis and the movements made by the child on the left axis. The black boxes on the diagonal represent the percentages of mirror-matching movements, the most frequent type of imitation for each model movement. The grey boxes represent the percentages of other types of imitation movement whose frequency of appearance deviated significantly from 0. The transparent boxes represent percentages of types of imitation movement appearing with statistically insignificant frequency.

pointing to them with her index finger. If the assumption regarding the elicitation of the motor programme most strongly associated with the main goal is correct, then we would expect the same error pattern as in the dot experiment (or as in the standard experiment). This should be true for both the control and the experimental condition. Conversely, we would expect that with grasping, children would use their dominant hand more frequently, because that is the hand most frequently used for grasping. In the control condition we would not expect such a tendency for the dominant hand, because we did not observe it in the dot experiment (experiment 3 in Bekkering *et al.* (2000)). We thus predict that in the grasping condition (not in the pointing condition), errors would increase in the cases in which the tendency to use the dominant hand for grasping coincides with the tendency to reach for objects with the ipsi-lateral hand. For right-handed subjects, this condition is met when the model grasps an object on its left side contra laterally with its right hand. In that case, the object is located to the right of the child, and he or she should almost inevitably be driven to use his or her right hand to grasp the object ipsi laterally.



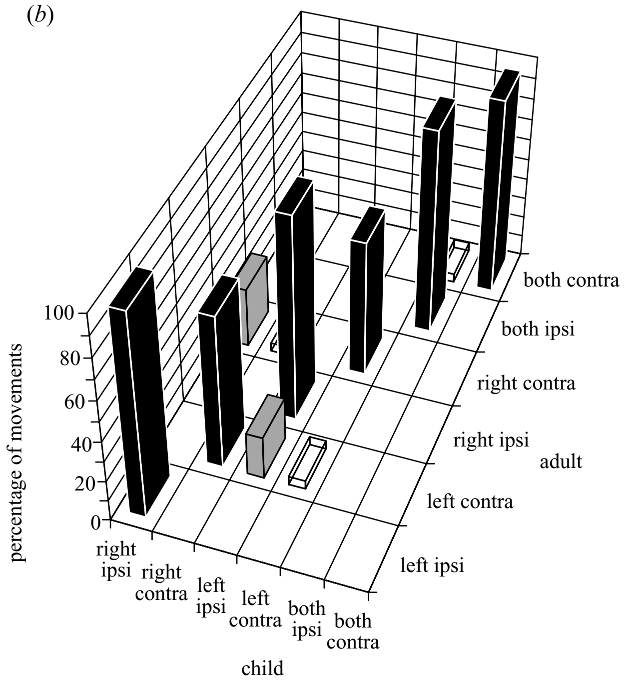


Figure 5. The movements made by the adult model on the right axis and the movements made by the child on the left axis. (*a*) The results of the grasping condition, in which the model as well as the children grasped and lifted the objects on the table. (*b*) The results of the pointing condition, in which the model as well as the children only pointed towards the objects on the table. The black boxes on the diagonal represent the percentages of mirror-matching movements, generally the most frequent type of imitation, but not for every model movement in the grasping condition. The grey boxes represent the percentages of other types of imitation movement occurring with a frequency that deviated significantly from 0. The transparent boxes represent a type of imitation movement appearing with statistically insignificant frequency.

Figure 5 shows the frequency of each of the six imitated movements for each model movement in both conditions. We arranged both diagrams in such a way that the mirror-matching movements are on the diagonal, although now it was only in the pointing condition that for each model movement mirror-matching movements were the most frequent movements imitated. In the grasping condition, children generated 100.0%, 50.0%, 66.7%, 25.0%, 100.0% and 79.2% mirror-matching movements when presented with the left-ipsi, left-contra, right-ipsi, right-contra, both-ipsi and both-contra model movements, respectively.

Children produced an average error rate of 30.6%. Four types of error occurred with significant frequency: left-handed ipsi-lateral imitation of the left-handed contra-lateral movement (50.0%), right-handed contra-lateral imitation of the right-handed ipsi-lateral movement (33.3%), right-handed ipsi-lateral imitation of the right-handed contra-lateral movement (75.0%), and bimanual ipsi-lateral imitation of the bimanual contra-lateral model movement (20.8%). With bimanual contra-lateral model movements, we made an unexpected observation. Children sometimes grasped the objects ipsi laterally and then, after lifting, crossed their arms while still holding the objects. This type of imitation was treated as 'correct' imitation. One-third of the correct imitations of bimanual contra-lateral model movements were imitated in this unexpected way. Despite these errors, children always grasped the correct object. Three of these error types were CI-errors and the fourth was an IC-error. Unimanual CI-errors (average 62.5%) were more frequent than bimanual CI-errors ($T'_0 = 0$, $N_0 = 5$, $p = 0.05$). In addition, unimanual CI-errors were more frequent when the child used the right hand (75.0%) than when he or she used the left hand (50.0%) for imitation ($T'_0 = 0$, $N_0 = 5$, $p = 0.05$).

In the pointing condition, children generated 100.0%, 75.0%, 100.0%, 66.7%, 100.0% and 95.8% mirror-matching movements when presented with the left-ipsi, left-contra, right-ipsi, right-contra, both-ipsi and both-contra model movements, respectively. Children produced an average error rate of 10.4%. Only two types of error occurred with significant frequency: left-handed ipsi-lateral imitation of the left-handed contra-lateral movement (20.8%) and right-handed ipsi-lateral imitation of the right-handed contra-lateral movement (29.2%). These two error types were the unimanual CI-errors. Hence, despite these errors, children always pointed to the correct object. The CI-errors (average 30.6%) were as frequent for the child's left-handed as for the child's right-handed movements ($T'_0 = 8$, $N_0 = 7$, $p = 0.133$, Pratt's exact test).

When compared with the pointing condition, the overall error rate of the grasping condition was significantly higher ($u = 2.04$, $p = 0.05$). All four error types of the grasping condition had a higher error rate when compared with the respective error types in the pointing condition. The rate of the bimanual CI-error in the pointing condition did not significantly deviate from zero. The IC-error in the grasping condition was not observed in the pointing condition. The right-handed CI-error rate was significantly higher in the grasping condition than in the pointing condition ($u = 1.86$, $p = 0.05$). Concerning the left-handed CI-error rate, there was no significant difference between the two conditions ($u = 1.48$, $p = 0.69$).

The experiment clearly confirmed another prediction of GOADI. Once the imitator has identified the goal of the model act, this goal elicits the motor programme most strongly associated with it. When imitating the grasping of objects (or the pointing towards objects), children always grasped (or pointed to) the correct object. Thus, as expected, the treatment of the object (grasping or pointing to) was the highest goal in the hierarchy. More important, however, is the fact that when we used grasping rather than pointing as the model act, the children showed a clear preference for using the dominant right hand. Such a preference was neither observed in any of the previous experiments, nor in the pointing condition. The preference for the right hand led to a strong increase (of *ca*. 45% when compared with the standard experiment or to the pointing condition) in the error rate for the condition in which the preference for the right hand met the preference for ipsilateral movements: the imitation of a right-handed, contra-lateral model movement.

This preference for the dominant right hand in the grasping condition received very strong corroboration by an unexpected finding. The preference was so strong that the children even produced a significant portion of errors in a condition in which they had shown no (or almost no) errors, either in the previous experiments or in the pointing condition. When the adult ipsi laterally grasped the object to her right, children quite frequently (in one-third of the cases) contra laterally grasped the corresponding object (which was located to their left) with their right hand. In this case, the preference for the dominant hand was obviously sometimes even stronger than the preference for ipsi-lateral movements. No such tendency was observed in the pointing condition.

Another unexpected finding also confirms GOADI and is a nice illustration of our theory of GOADI. When the model grasped both objects with crossed arms, children ended up in 80% of the cases by holding the two objects with crossed arms. This is not a surprise, because it is in line with our previous findings. However, in one-third of these cases, the children first grasped the objects ipsi laterally and only afterwards crossed their arms. This unexpected finding shows that the model's act was decomposed into a main goal (grasping both objects) and a sub-goal (crossing the arms). The main goal then was pursued first, followed by the pursuit of the sub-goal. In that sequence, which was, however, reversed with respect to the model's act, both the main goal and the sub-goal elicited the motor programme most strongly associated with their achievement.

5. IMITATION IN ADULTS

The theory of GOADI is thought to be valid for all individuals, irrespective of age and developmental state. Hence, one should be able to show the same pattern of imitation 'errors' in adults. Of course, in such simple tasks as touching the contra-lateral ear, we do not expect adults to show the same overall level of errors that we found in children. Nevertheless, if the goal-directed theory of imitation is generally valid, some (probably weaker) effects in adult's imitation behaviour should be detectable. This was indeed the case in a speeded response version of the hand-to-ear task in adults: adults also showed significantly ($T'_0 = 7$, $N_0 = 10$, $p < 0.05$) more CI-errors than IC-errors (see figure 6).

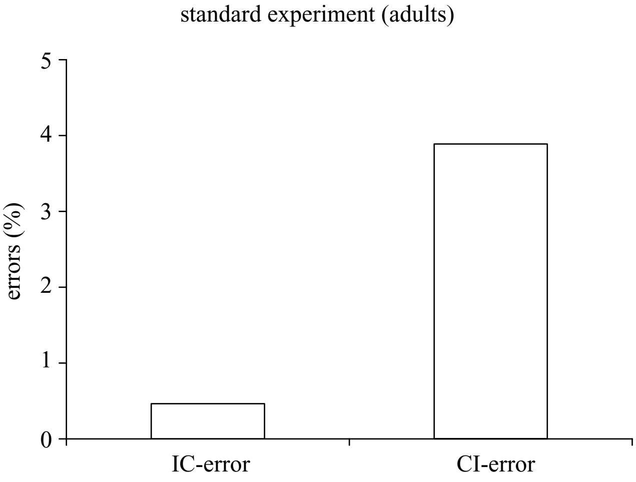


Figure 6. The amounts of IC-errors and CI-errors adults made in a unimanual speeded response version of the standard hand-to-ear task. Stimuli were presented on a computer monitor and the hand movements were recorded using a magnetic positioning system (Polhemus Fastrak).

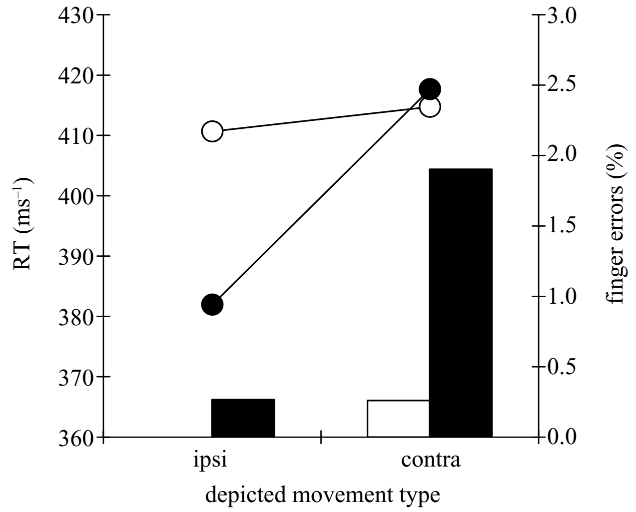


Figure 7. Results of the covering-dots experiment in adults. Imitating contra lateral was slower (lines) and more finger errors (columns) were made, but only if dots were present. Black circles represent with-object results; open circles represent without-object results.

We also replicated another one of our core experiments—covering dots on a table—in adults (see Wohlschläger & Bekkering 2002*a*), expecting to find a reflection of the children's error pattern at a lower level in adults and in their RTs. To be able to measure RTs precisely, we slightly modified the task. First, we used finger movements instead of whole hand movements. Second, the model movements were not presented by the experimenter but on a computer screen. Subjects were instructed to put their hands next to each other on the table and to imitate the depicted downward finger movement as quickly as possible after the presentation of one of the stimuli. As in the experiment with children, there were two conditions. In one condition, the stimuli contained two dots, one of which was covered by one of the fingers at the end of an

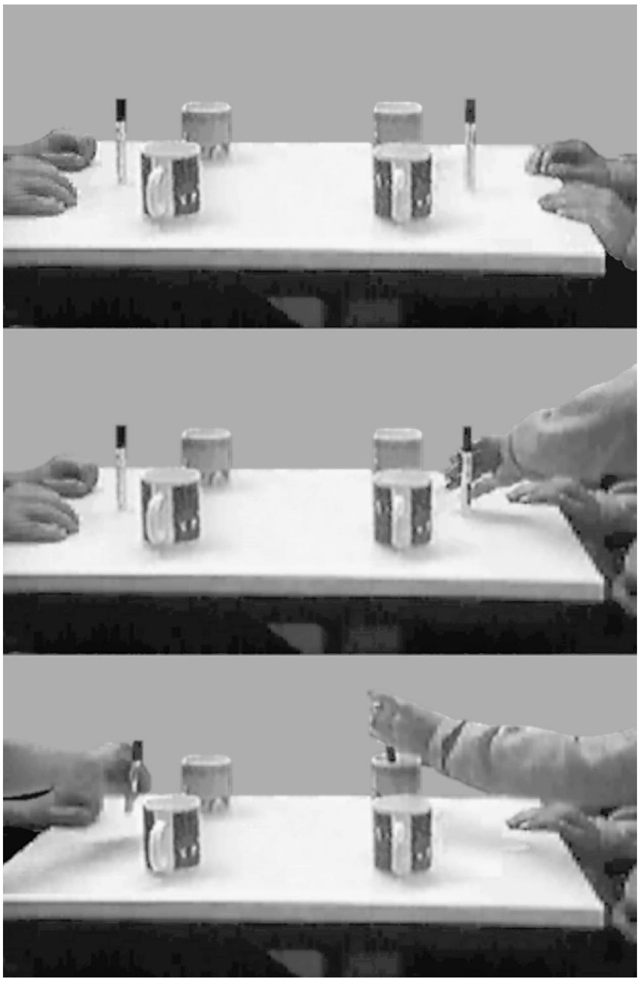


Figure 8. Three frames of an imitation sequence used for adults. The model on the right uses the left hand to put the pen upside down into the right cup by turning it counter-clockwise. The imitator uses the right hand and turns the pen clockwise to put it into the left cup (not shown). In this example, the imitator perfectly mirrored the model movement. However, most subjects failed to do so. For details see text.

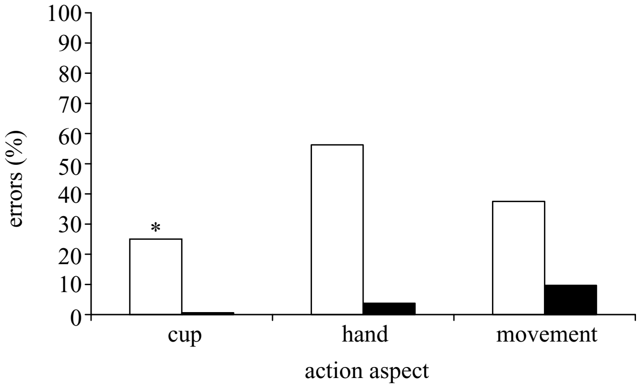


Figure 9. Spontaneous (open bars) and repeated (black bars) imitation of an action with three aspects in adults. The asterisk indicates spontaneous errors significantly below chance level (50%). For details see text.

either ipsi-lateral or contra-lateral downward movement. In the other condition, the stimuli depicted the same movements, but no dots were present.

Results showed that, although adults make almost no errors (0.6%), these few errors mainly (77.8%) occur with stimuli depicting contra-lateral movements towards dots (CI-error). Second, RTs were faster for ipsi-lateral movements, but only if dots were present (see figure 7). These and the above results from the hand-to-ear task, which basically replicate the findings in children, show that in adults dots also as action goals are activating the direct, ipsi-lateral motor programme, which leads to faster responses and sometimes even to errors.

Although adults show the same pattern of errors as children in simple actions, more complex actions are needed to investigate the *general validity* and the *hierarchical organization* of our goal-directed theory of imitation. In the experiments reported above, the actions comprised only two variable aspects: the goal object and the effector. It transpired that an increase to three variable and independent aspects (goal *object*, *effector* and *movement path*) is sufficient to cause considerable amounts of errors also in adults.

The action we used was more complex but nevertheless quite simple. It consisted of moving a pen upside down into one of two cups (*object*). In either case, the pen was rotated by 180°. The experimenter served as the model and he either used his right or his left hand (*effector*). In addition, he either turned the pen clockwise or counter-clockwise (*movement path*) to bring it into an upside-down position at the end of the movement (see figure 8).

In a pilot study, we did not tell the subjects about the three different aspects of the movement, because we wanted to find out which hierarchical order the subjects apply spontaneously. However, an analysis of the errors revealed that although subjects start with the expected hierarchy (least errors with object followed by effector followed by movement path), after some tens of trials, they reordered their hierarchy individually, always in favour of one aspect at the cost of the others. Hence we decided to fully explain the experiment to the subjects, except for the very first trial. In the first trial, the experimenter made one of the eight possible movements without instructing the subjects to imitate. Instead he asked, 'Kannst Du das auch?' ('Can you do that too?'). Only after the first trial were subjects fully instructed about the purpose of the experiment and about each individual aspect of the movement by stressing that it was important to imitate all aspects as precisely as possible. Thus, we could analyse and compare spontaneous imitation with repeated imitation.

Results (see figure 9) showed that in spontaneous imitation the only aspect that was imitated correctly above chance level was the object (binomial probability $p < 0.05$). Likewise, the object was imitated most correctly, followed by the effector, followed by the movement path in repeated imitation (linear contrast: $t = 1.98$, d.f. $= 7$, $p < 0.05$). Obviously, the goal of an action is so strong that the other aspects of an action are more or less neglected, even if the subject knows explicitly about all aspects and tries his/her best to copy all of them as exactly as possible.

In a further series of experiments, we increased the number to four variable aspects: the goal *object*, the *treatment* of the object, the *effector* and the *movement path*. We

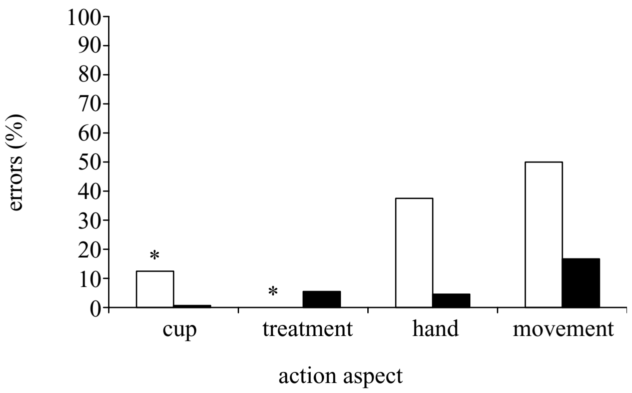


Figure 10. Spontaneous (open bars) and repeated (black bars) imitation of an action with four aspects in adults. The asterisks indicate spontaneous errors significantly below chance level (50%). For details see text.

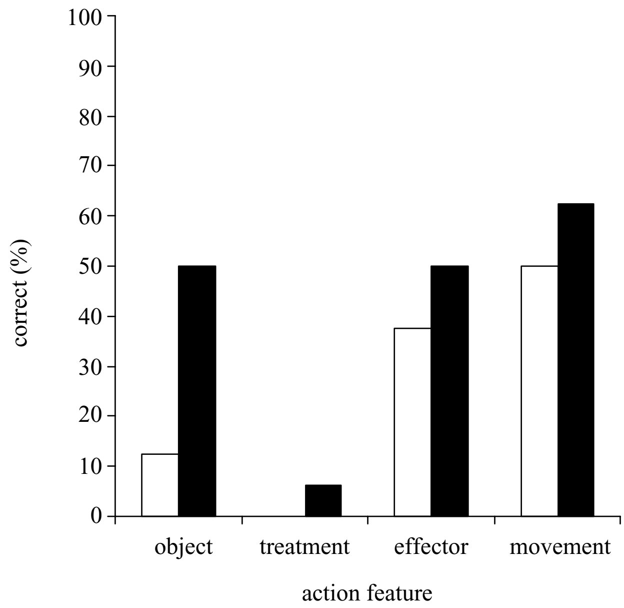


Figure 11. Spontaneous imitation of an action with four aspects in adults. Open bars: objects differ in both colour and location; black bars, objects differ in location only. For details see text.

added the fourth aspect—treatment—because the corresponding experiment in children (grasping versus pointing, see above) showed that apart from the object itself, its treatment plays a decisive part for imitation behaviour. Again, in repeated imitation, subjects showed the least errors with respect to the object, followed by treatment, followed by effector and followed by movement (linear contrast: $t = 4.16$, d.f. $= 15$, $p < 0.01$). As predicted, the only aspects that were imitated correctly in spontaneous imitation were the object and its treatment (binomial probability: $p < 0.001$; see figure 10 for the results). A control task showed that the differential effects in repeated imitation were not due to perceptual deficits. When we blocked the trials in such a way that in each block only one aspect varied while the others were held constant (subjects were informed about the varying aspect at the beginning of each block), subjects showed approximately the same amount of errors for every aspect. In spontaneous imitation, however, we could show that the choice of the object is indeed a choice for object identity and not for object location. When using four cups of the same colour (*not* as in figure 8), so that the objects only differed by location, only treatment was left as the single aspect that was imitated correctly above chance level (Wohlschläger & Bekkering 2002*b*; figure 11).

6. CONCLUSIONS

The experiments we have reported demonstrate the importance of objects and their treatments in human imitation, both for children and adults. The experiments widely confirmed our theory of GOADI. They showed that it is primarily the treatment of an object that is imitated in object-oriented actions, whereas the choice of the effector and the movement path are following the so-called *ideomotor principle*: the motor programme most strongly associated with the achievement of the goal is executed during the execution of the imitative act and it is probably already activated during the observation of the action that is imitated later (Fadiga *et al.* 1995). The study of brain activity during the covering-dot task (Wohlschläger & Bekkering 2002*a*) in adults recently showed that the human homologue of the monkey's mirror-neuron area is more active during the imitation of object-oriented than non-object-oriented actions (Koski *et al.* 2002). Hence, one may conclude here that there is a mirror-neuron-system in humans too, and that it is used for imitation. This does not mean that the mirror-neuron system is doing the imitation: despite the fact that it was discovered in monkeys, monkeys do not imitate. However, when conceiving imitation as an imitation of the goals of an action, then it makes sense that the mirror-neuron system is involved in imitation, because it is essentially a system for representing actions (irrespective of whether just observed or executed) in terms of action goals, i.e. object plus treatment.

According to GOADI and confirmed by the data presented above, actions involving objects are imitated in such a way that the same treatment is given to the same object, thereby ignoring the motor part of the action. Of course, in everyday life the model acts in an efficient and direct way on the object. If the imitator copies the action goal and if this action goal in turn activates the most direct motor programme in the imitator, then both actions resemble each other in all aspects, leading to an impressive, mirror-like behaviour. When there is no object, the movements themselves become the goal and they are also imitated in a mirror-like fashion. It is probably the frequently observed parallelism between the movements of the model and the imitator that led to direct-mapping theories. However, according to GOADI, this similarity between the movements of the model and the imitator is only superficial and incidental: the underlying similarity is a similarity of action goals.

Imitating goals and/or intentions of course requires that the imitator understands the action of the model. In our view, action understanding is a prerequisite for imitation. It is a necessary but not a sufficient condition for imitation to occur. Within a goal-directed theory (as opposed to direct-mapping explanations) it is possible to explain why imitation sometimes occurs and sometimes does not. *Because* action understanding precedes imitation the observer can decide whether or not he wants to imitate the goals of the model. In addition, a goal-directed theory of imitation also gives room for creativity in imitation, because the way the goal is achieved is left to the imitator, whereas direct-mapping approaches have a rather automatic taste. When the model observes the imitator achieving the same goal in a more efficient way it might, in turn, cause the model to imitate the new movement of the former imitator. This type of creativity, based on the decoupling of ends and means and on mutual imitation, probably plays a very important part in the evolution of culture and technique.

Although using action goals as the core concept, GOADI does not say anything about the representation of the intentions of the model in the imitator. In our view, the representation of intentionality or any theory of mind is not necessary to explain imitation (see Gattis *et al.* (2002) for a different interpretation). We have so far only investigated rather simple actions. However, GOADI could also be applied to more complex actions and action sequences. Byrne's (2003) concept of 'imitation as behaviour parsing' is very close to our theory of GOADI. Byrne also assumes that the elements of an action sequence that will be learned by imitation have to already be in the repertoire of the observer. This corresponds to GOADI's ideomotor principle. His studies of imitation in gorillas also show that the actual movement is less important than the action outcome (e.g. the hand the imitator uses does not depend on the hand the model uses; Byrne & Byrne 1991).

Although the experiments reported here widely confirm GOADI and, at the same time, illustrate the shortcomings of the AIM theory of Meltzoff & Moore (1994), some sort of mapping mechanism must still be involved in imitation. The ability to identify limbs and body parts and to map those to the parts of our own body is perhaps inborn. AIM is primarily based on imitation performances in neonates. Presumably, neonates need to develop successful GOADI behaviour by learning through experience. In fact, our theory may require the assumption of a coarse direct limb-to-limb mapping, But it is probably only a coarse mapping of visual input to motor output, because neither the side of the body, nor the number of effectors, nor even the type of movement is consistently mapped. In addition, and as already noted above, the direct-mapping approaches hold the notion of automaticity and mainly address the question of how the input is translated into a motor output matching the input. They do not address more complex questions such as when imitation occurs, or who imitates whom. GOADI does not (yet) address these questions either; but it is open to that meta-level of imitation, because it uses action goals as the central explanatory component. Thus, by using GOADI one can easily build a hypothesis about the meta-level of imitation. For instance, one might speculate that the minimum necessary condition for the occurrence of imitation is that the goal of the model's act is within the range of the imitator's desires.

The differentiation between goals and sub-goals (or ends and means) parallels the distinction made by Tomasello *et al.* (1993) between emulation and imitation. Whereas emulation refers to the reproduction of the goal, imitation also includes the reproduction of the model's strategies for achieving the goal. By contrast, Byrne & Russon (1998) argue that it is the complexity of the goal hierarchy that decides whether almost all aspects of an action (programme-level imitation) or only a few of them (action-level imitation) are imitated.

Let us now turn to some of GOADI's implications. First, GOADI has adaptive implications. In general, a model and its imitator have different body and limb sizes, which results in differences in their dynamic properties. In addition, they usually also differ in their available motor skills. Thus, for the imitator, it is more reasonable to concentrate on the goal of a movement and try to reach it somehow in his own manner (perhaps even with several trials), and it is less reasonable to focus on the course of the movement. A second and more practical implication concerns teaching. Teachers who want to teach by imitation should keep in mind that it is probably more useful to demand the achievement of the ends rather than the means from their pupils. When they serve as models, they should encourage pupils to focus on the goal, rather than on the movement. Recent research results recommend this method for the acquisition of motor skills (Wulf 1998).

In summary, the experiments reported here widely confirm the assumptions of GOADI. We assume that there is no principle difference in imitation behaviour between children and adults beyond the fact that children probably have a smaller working memory capacity and hence disregard more aspects of a model's movement than adults do.[4]

We thank Brigitte Gleißner and Monika Benstetter for the conduction of the experiments and Megan Otermat for proofreading.

ENDNOTES

[1]Anisfeld (1996) argues that if infants' imitative behaviour is restricted to a single gesture, it is perhaps more parsimonious to explain it as a specific, directly elicited response. The increase in tongue protrusion after modelling might also be explained by its inhibition during the attentive observation of the model (Anisfeld 1991).

[2]By 'inferring the intention of the model', we do not want to imply that the imitator has an explicit representation of the model's intention as a mental state of the model. This question is mainly relevant for predicting the action outcome of one's conspecifics but it is irrelevant for imitating it.

[3]Though theoretically possible, there were no double errors.

[4]For example, when asked to imitate the cross-lateral, bimanual hand-to-ear movement, adults of course imitate correctly, but—unless this aspect is drawn to their attention—they do not care which arm is in front.

APPENDIX A: SONG TEXT

Boys' version

Auf der Wiese, auf der Wiese
Läuft ein kleiner Mann.
Hat zwei Hände, hat zwei Füße,
Läuft so schnell er kann.

Girls' version

Auf der Wiese, auf der Wiese
Läuft 'ne kleine Frau.
Hat zwei Hände, hat zwei Füße,
Läuft so schnell sie kann.

(Refrain):
Läuft ganz schnell im Kreis herum,
Fällt dabei auch gar nicht um.
Schau den kleinen Mann mal an,
Was der Mann noch alles kann:

(Imitation)
Auf der Straße, auf der Straße
Läuft der kleine Mann.
Hat zwei Augen, Mund und Nase,
Läuft so schnell er kann.
(Refrain, Imitation)
In die Pfütze, in die Pfütze
Läuft der kleine Mann.
Auf dem Kopf hat er 'ne Mütze,
Läuft so schnell er kann.

(Refrain, Imitation)

Text: Andreas Wohlschläger
Tune: Brigitte Gleissner

(Refrain):
Läuft ganz schnell im Kreis herum,
Fällt dabei auch gar nicht um.
Schau die kleine Frau mal an,
Was die Frau noch alles kann:

(Imitation)
Auf der Straße, auf der Straße
Läuft die kleine Frau.
Hat zwei Augen, Mund und Nase,
Läuft so schnell sie kann.
(Refrain, Imitation)
In die Pfütze, in die Pfütze
Läuft die kleine Frau.
Auf dem Kopf hat sie 'ne Mütze,
Läuft so schnell sie kann.

(Refrain, Imitation)

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GLOSSARY

AIM: active intermodal mapping
CI-errors: contra-ipsi-errors
GOADI: goal-directed imitation
IC-errors: ipsi-contra-errors
RT: response time